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Biogas as a sustainable energy source for developing countries: Opportunities and challenges

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A B S T R A C T

Energy is an indispensable part of modern society and can serve as one of the most important indicators of socio-economic development. Despite advancements in technology, however, some three billion people, primarily in the rural areas of developing countries, continue to meet their energy needs for cooking through traditional means by burning biomass resources (i.e., firewood, crop residues and animal dung) in crude traditional stoves. Such practices are known to be the source of significant environmental, social, economic and public health issues. To achieve sustainable development in these regions, it is imperative that access to clean and affordable (renewable) energy is made available. Within this context, upgrading existing biomass resources (i.e., animal manure, crop residues, kitchen waste and green wastes) to cleaner and more efficient energy carriers (such as biogas from anaerobic digestion) has unique potential to provide clean and reliable energy, while simultaneously preserving the local and global environment. In spite of its significant potential to serve developing nations, however, the high costs and lack of expertise in installation and maintenance of biogas technology preclude widespread adoption in geographically isolated communities. Concerted efforts from both governmental and non-governmental sectors are absolutely essential in facilitating modernization and dissemination of biogas technology to harness the inherent potential that is currently underutilized and unexploited. The intent of this paper seeks to highlight the present status, challenges, and potential of biogas technology to advocate for further research, development and dissemination of the concept in developing countries.

Contents

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1. Background

Energy is an indispensable part of our daily life, often taken for granted by populations which enjoy the comforts of modern society. Despite the continually rising energy demands reported globally, however, millions of communities and households, particularly in developing countries, still lack access to basic energy services such as electricity, liquid fuels, and natural gas. For example, about 1.5 billion people (over 20% of the world population) do not have electrical power, and approximately 3 billion people (some 45% of the world population) rely on solid fuels such as firewood, crop residues, cattle dung, and coal to meet their cooking needs (Tables 2 and 3) [1]. Further, the number of households depending on traditional solid fuels is increasing as the population growths in Sub-Saharan Africa (SSA) outpaced the number of new electrical connections [2–4]. With the absence of new policies to support access to modern energy services, an additional 50–220 million people in developing countries will rely on traditional solid fuels and stoves by 2030, compared to in 2005 [5]. Biomass, which comprises 10–14% of the total global energy demand [6], accounts for over 90% of household energy consumption in many developing countries [7]. Although governments in some of these nations annually spend between 40–60 billion US dollars on the installation of power infrastructure [8], the vast majority of the people in these regions remain disconnected from the grid (Table 3) [1]. Additionally, per capita energy consumption – often viewed as part of the development index – is very low (<1.0 tonne of oil equivalent (toe)/year) in developing countries compared to over 4.0 toe/year in developed countries [9]. For most of developing and SSA countries like Nepal, India, Kenya, and Ghana, the per capita total primary energy supply (TPES) is 0.34 toe/year, 0.54 toe/year, 0.47 toe/year, and 0.41 toe/year, respectively; far less than the world's average per capita TPES of 1.83 toe/year [9].

As the aforesaid countries continue to grow and urbanize, waste management will be a major issue at the local and national levels [10]. In developing and underdeveloped countries in particular, a lack of effective and efficient solid waste and sewage management systems pose a significant threat to human health and the environment. In Asia alone, waste generation has reached 1 million dry tons per day [11]; up to 70% of municipal solid waste (MSW) is comprised of organic matter [12]. Despite large expenses on infrastructure, the urban areas of most developing countries are still grappling with the challenges of preventing irreparable environmental damage [11]. The absence of sustainable management of organic fractions in MSW is already responsible for various ecological problems such as soil, surface and groundwater pollution from the leachate as well as uncontrolled methane (CH_4) emissions; a potent greenhouse gas (GHG) [12].

Recently, the world energy council and the United Nations (UN) commission on sustainable development have reiterated the need for affordable, clean and renewable energy to enhance sustainable development [13]. Further, the UN declared 2012 as the 'international year of sustainable energy for all' which had the objective of providing universal access to modern energy by 2030 [14]. In this context, the use of existing biomass such as kitchen waste, cattle dung, crop residues, green wastes, and the organic fraction of industrial and municipal wastes for producing clean and renewable energy through anaerobic digestion (AD) in developing countries would improve human health, the local environment and the socio-economic conditions [15]. AD is a biological process that converts organic matter into energy-rich biogas in the absence of oxygen. Biogas – a mixture primarily consisting of CH_4 and CO_2 – can be used as a clean renewable energy source for cooking, generating heat and electricity, and can be upgraded into biomethane for use as a transportation fuel as well. Biogas digestate, a nutrient-rich residue following digestion, can be used as a soil conditioner and/or organic fertilizer. Thus, AD can play a significant role in addressing all of the aforementioned concerns plaguing underdeveloped and developing nations (i.e., energy and waste management) while simultaneously increasing agricultural productivity [16].

This manuscript seeks to highlight the current situation of energy use in developing countries and elucidates the role that AD for biogas production can and does play in meeting the energy and waste management needs of these regions. Although a detailed discussion on the basics of AD can be found elsewhere [16]; a brief description is included to build a foundation for subsequent sections. This paper includes a general discussion on biogas production process, its composition and applications, and further reviews the available biomass resources in developing nations, their biogas production potential and subsequent GHG emission reduction potential. AD is a mature technology, and consequently an emphasis has been placed on the current status of biogas, but in many cases AD technologies in developing countries remain crude. The manuscript concludes with recommendations for the development and adoption of biogas technology as a sustainable energy source in developing countries.

2. Biogas: production, composition and applications

2.1. Biogas production

The conversion of organic matter into biogas is carried out by a consortium of microorganisms through a series of metabolic stages (namely, hydrolysis, acidogenesis, acetogenesis and methanogenesis) (Fig. 1). In the first step, complex organic compounds such as lipids, proteins, and polysaccharides are converted into soluble monomers or oligomers (e.g. amino acids, long chain fatty acids, sugars and glycerol) through hydrolysis, also known as liquefaction. This process is facilitated by hydrolytic or fermentative bacteria that release extracellular enzymes. The simple soluble

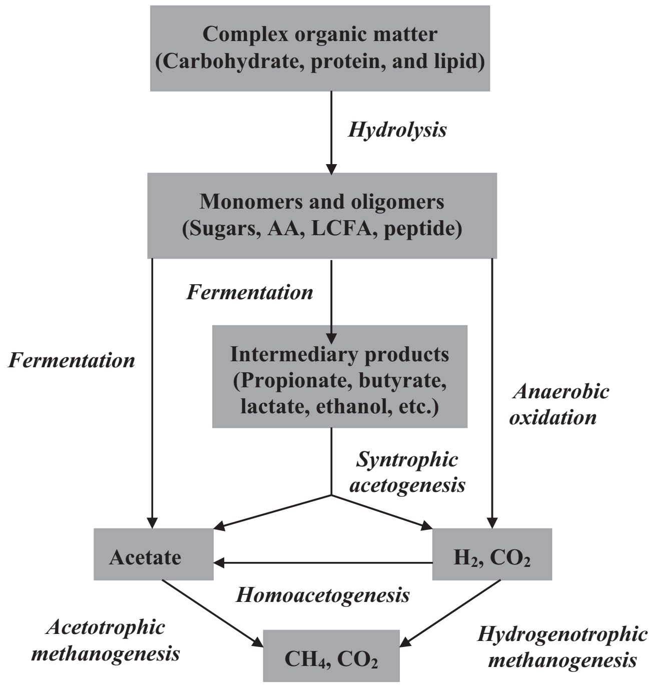

Fig. 1. Major stages of biomethanation process. (AA=amino acids; LCFA=long-chain fatty acids). *Modified from Khanal* (2008) [16].

compounds are then fermented by acidogenic bacteria into a mixture of carbon dioxide (CO_2), hydrogen (H_2), alcohol, and low molecular weight volatile fatty acids (VFAs), e.g. propionic and butyric acids; a process known as acidogenesis.

During acetogenesis, alcohols and VFAs are anaerobically oxidized by hydrogen-producing acetogenic bacteria into acetate, H_2 and CO_2. Acetate can also be formed from H_2 and CO_2 by hydrogen-oxidizing acetogenic bacteria known as homoacetogens. The homoacetogenesis process has not been widely studied or characterized [16].

In the final stage, acetotrophic and hydrogenotrophic methanogens transform acetate, H_2 and CO_2 into a mixture of CH_4 and CO_2. Acetotrophic methanogens utilize acetate as a substrate in a process known as acetotrophic methanogenesis. The hydrogenotrophic methanogens reduce CO_2 by using H_2 as an electron donor in a process called hydrogenotrophic methanogenesis. Of the total CH_4 produced, about 70% originates from the decarboxylation of acetate, while the remaining CH_4 is mostly produced from CO_2 reduction [17–19]. Small amounts of CH_4 are also produced from formic, propionic and butyric acids, and from other organic substrates by methanogens [20]. It is important to point out that for high solids feedstocks, hydrolysis is the rate-limiting step. For highly soluble feedstocks, methanogenesis is the rate-limiting step.

Anaerobic processes divert a small amount (about 14%) of the available energy for microbial growth (10% for fermentative bacteria, and 4% for methanogens), and most of the energy (about 86%) is stored in the end product, CH_4 [21,22].

2.2. Biogas composition

The composition of biogas varies with type of feedstock and operating condition of the digester. In general, biogas consists of 50–75% CH_4 and 25–50% CO_2 along with other trace components like water vapor (H_2O), hydrogen sulfide (H_2S), and ammonia (NH_3). Typical compositions of raw biogas and the properties of the components are summarized in the Table 1.

CH_4 is the only component of biogas that contributes to the heating value. For example, 1 m^3 of raw biogas at standard temperature and pressure containing 60% CH_4 has a heating value

Table 1
Chemical composition of biogas and properties of components [23].

Components	Concentration	Properties
CH_4	50–75% (v/v)	Energy carrier
CO_2	25–50% (v/v)	Decrease heating value Corrosive, especially in presence of moisture
H_2S	0–5000 ppm(v/v)	Corrosive Sulfur dioxide emission during combustion
NH_3	0–500 ppm(v/v)	NO_x – Emissions during combustion
N_2	0–5% (v/v)	Decreases heating value
Water vapor	1–5% (v/v)	Facilitate corrosion in presence of CO_2 and sulfur dioxide (SO_2)

21.5 MJ (5.97 kWh of electricity equivalent) compared to 35.8 MJ (9.94 kWh electricity equivalent) per m^3 of pure CH_4 at standard temperature and pressure [24].

2.3. Biogas applications

Biogas is renewable energy carrier with a potential for diverse end-use applications such as heating, combined heat and power (CHP) generation, transportation fuel (after being upgraded to biomethane) or upgraded to natural gas quality for diverse applications. In developing countries mainly with household-scale digesters, however, the end use of biogas is primarily limited to cooking and lighting. This is because the most common digester in the developing countries is of 2–10 m^3 size, and the volume of biogas produced from such digester cannot accommodate CHP or purification into biomethane for other end-use purposes. It should be noted that biogas produced from large-scale institutional plants in some developing countries, however, is being used for electricity generation through fuel cells or CHP engines; similar to technologies found in developed countries. For example in Pura, India a community biogas digester was successfully used to power a modified diesel engine and run an electrical generator [25]. Perhaps most importantly, cooking accounts for a notable fraction of household energy consumption in developing countries. For example, in India, cooking comprises 60% of the total national energy consumption [26]. In these regions, cooking is primarily carried out in traditional cook stoves by burning traditional solid fuels, which ultimately results poor energy use efficiency. For example, in Bangladesh, more than 90% of families use mud-constructed cook stoves with a thermal efficiency of only 5–15% [27]. In contrast, methane (in biogas) burns with a clean blue flame that is much hotter than fire fueled by traditional resources [28]. Depending upon the design and operating conditions, the efficiency of biogas cook stoves in developing countries may range from 20–56% [28,29] and operates satisfactorily under gas pressures of 75–85 mm of water, with biogas consumption of about 0.22–1.10 m^3 per hour [30]. For Nepal, it has been estimated that 0.33 m^3 of biogas is required to fulfill the cooking needs per capita per day [30].

Lighting is the second most common end use of biogas after cooking, especially in the regions without electrical grid connection. Biogas is implemented for lighting by using special gas mantle lamps, which typically consume about 0.07–0.14 m^3 of biogas per hour and function satisfactorily under a gas pressure of 70–84 mm of water [30].

3. Merits of anaerobic digestion

3.1. Health benefits

In rural areas of developing countries, some three billion people rely on biomass such as fuel wood, crop residues and animal dung,

and charcoal to meet their energy needs for cooking [1]. In many countries, these resources account for over 90% of typical household energy consumption. Additionally, 30–95% of the total energy used originates from households compared to 25–30% in the developed countries [31]. Direct burning of biomass in traditional cook stoves results higher emissions of carbon monoxide, hydrocarbons, and particulate matters [32–34]. Since cooking is usually performed indoors without proper ventilation, this can and does result in severe health issues due to indoor air pollution (IAP). Evidence on the use of solid fuels and the occurrence of diseases like child pneumonia, chronic obstructive pulmonary disease (COPD), and lung cancer has been reported in several developing countries [35,36]. Moreover, studies have linked IAP exposure to a variety of other health problems, such as asthma and cataracts [33], low birth weight and stillbirth [37], tuberculosis [38], and high blood pressure [39] among others. The World Health Organization (WHO) estimates that 1.5 million premature deaths per year (over 4000 deaths/day) are directly associated with IAP from the use of solid fuels. Among the 1.5 million deaths per year, more than 85% (about 1.3 million people) are attributed to biomass use, the rest are due to coal use [34]. Importantly, women and children suffer the most from IAP because they are traditionally responsible for cooking and other household chores which involve spending hours by the cooking fire, and prolonged exposure to smoke.

Unlike firewood, crop residues and dried cattle dung, biogas provides a clean, smoke-free environment. Consequently, the widespread installation of biogas facilities (both large and small scale) could significantly help in reducing IAP, and lower incidences of IAP linked diseases. In addition, because the installation of biogas technologies require households to construct toilets (construction of toilet is mandatory by most of the subsidy programs that are promoting household biogas plants in developing countries), the current issue of open defecation (in developing countries) which is largely responsible for cholera, typhoid and other water borne diseases will be minimized.

Table 2
Number of people relying on solid and modern fuels for cooking for Least Developed Countries (LDCs) and Sub-Saharan Africa (SSA) [1].

Region	No. of people relying on solid fuels (in millions)			No. of people with access to modern fuels (in millions)
	Traditional biomass	Coal	Total	
Developing countries	2564	436	2999	2294
Least Developed Countries (LDCs)	703	12	715	74
Sub-Saharan Africa	615	6	621	132

Note: Based on UNDP's classification of developing countries, and the UN's classification of LDCs. There are 50 LDCs and 45 SSA countries, with 31 countries belonging to both categories. Traditional biomass includes wood, charcoal, dung, straw, and crop residues. Modern fuels refer to electricity, liquid fuels, and gaseous fuels such as liquid petroleum gas (LPG), natural gas, and kerosene.

Table 3
Distribution of people relying on solid fuels for cooking and without access to electricity by the developing regions [1].

Region	% of people relying on solid fuels for cooking	% of people without access to electricity
Sub-Saharan Africa	21	39
Latin America and the Caribbean (LAC)	3	2
India	27	28
South Asia (less India)	11	14
East Asia Pacific (EAP) (less China)	11	13
Arab States	2	3
China	25	1

3.2. Environmental benefits

The extensive use of firewood for energy purposes, especially in developing countries, has a severe impact on local forests. According to Osei [40], fuel wood accounts for 54% of deforestation in developing countries. Worldwide deforestation is responsible for 17–25% of all anthropogenic GHG emissions [41], making it one of the leading causes of increased GHG emissions. In addition, deforestation plays an important role in soil erosion and land degradation [42]. Katuwal and Bohara [43] estimated that annually a household level biogas digester spares the direct burning of 3 metric tons (6600 pounds (lbs)) of firewood and 576 kg (kg) (1270 lbs) of dung; subsequently eliminating 4.5 metric tons (9900 lbs) of CO_2 emissions to the atmosphere. Therefore, a significant reduction in deforestation, particularly in developing countries, can be achieved by replacing firewood with biogas, ultimately mitigating GHG emissions.

3.3. Social/gender benefits

As discussed previously, in the majority of developing countries, women and children are responsible for firewood and dung collection which are both time consuming and exhausting tasks. For example, women and children in some places travel more than 5 km (3 miles) and spend nearly 6 hours a day gathering biomass and cooking food [44,45]. In addition to IAP, the labor is hard and can lead to back- and neck-pain as well as other physical ailments [42]. Because of these significant demands on time and labor, women and children are deprived of opportunities for education and other activities.

Based on a case study conducted in Nepal, a household biogas plant saves about 2 h per day of a woman and child's time. Most of the saved time has been used in recreational activities, social work, income-generating labor and education [43]. Thus the installation of biogas plants at the household level can directly provide increased and better opportunities for gender equality in rural areas of developing nations; the long-term social benefits of which may be significant.

3.4. Other emission reduction

Although AD is a more complex process compared to aerobic technologies for treating organic waste, significant amounts of energy can be recovered and exploited to benefit local communities. Both in terms of environmental as well as economic merits, AD is superior to composting, incineration or the combination of digestion and composting because of an improved energy balance and reduced emission of volatile compounds such as ketones, aldehydes, ammonia and methane [46,47].

3.5. Biogas slurry as organic fertilizer

In contrast to composting and direct burning, AD provides both fuel and fertilizer, rather than simply one or the other. The spent digested slurry (digestate) exiting the biogas plant remains rich in both macro- and micro-nutrients, and when applied to the land, enhances physical, chemical, and biological attributes of the soil as well as increases crop productivity. Due to improved flow properties, the digestate can penetrate into the soil faster which reduces the risk for nitrogen losses in the form of ammonia [48]. The digestate is also known to suppress soil borne pathogens by stimulating soil actinomycetes which produce antibiotics. In general the digestate contains N_2 (1.8%), P_2O_5 (1.0%), K_2O (0.9%), Mn (188 ppm), Fe (3550 ppm), Zn (144 ppm) and Cu (28 ppm).

Table 4
Nutrient contents of important organic manure.

Organic manure	Organic matter (%)	C:N ratio	N_2 (%)	P_2O_5 (%)	K_2O (%)	References
Farm yard manure	25–55	15–20	0.40–0.80	0.60–0.82	0.50–0.65	[50]
Biogas slurry	60–73	17–23	1.50–2.25	0.90–1.20	0.80–1.20	[50]
Vermicompost	9.80–13.40[a]	–	0.51–1.61	0.19–1.02	0.15–0.73	[51]

[a] Organic carbon.

Table 5
Number of domestic digesters in selected Asian and African countries [63].

Country	Year of program initiation	Number of digesters installed in the year		Cumulative up to 2012
		2011	2012	
Asia				
Nepal[a]	1992	19,246	17,988	268,464
Vietnam[b]	2003	23,372	28,635	152,349
Bangladesh	2006	5049	5555	26,311
Cambodia	2006	4826	4201	19,173
Lao PDR	2006	439	483	2888
Pakistan	2009	860	877	2324
Indonesia	2009	2970	3222	7835
Bhutan	2011	40	225	265
Africa				
Rwanda	2007	785	773	2619
Ethiopia	2008	1641	2511	5011
Tanzania	2008	1444	2409	4980
Kenya	2009	2399	3510	6749
Uganda	2009	1276	1181	3083
Burkina Faso	2009	609	1292	2013
Cameroon	2009	33	54	159
Benin	2010	20	22	42
Senegal	2010	225	95	334
Total Asia and Africa		**65,234**	**73,011**	**504,599**

[a] Including plants financially supported by World Wildlife Fund (WWF) since 2007; total 7915.
[b] Including plants under Asian Development Bank (ADB) and World Bank (WB) supported program since 2010; total 26,065.

A summary of the nutrient contents of the digestate and other organic manure is included in Table 4. Because human excreta contains higher amounts of plant nutrients than cow dung, the incorporation of human excreta as a feedstock can improve the overall nutrient qualities of the slurry, and if treated properly, the slurry can be utilized in agriculture as a complete fertilizer [49]. AD also results in a significant reduction of odors (up to 80%) of the crude feedstock [48].

However, spent slurries′ derivation (in part) from animal and/or human excreta may be of concern particularly when dealing with the large-scale loading, transportation, and distribution of the slurry in remote, underprivileged regions. Pathogenic microorganisms (e.g. *Salmonella, Listeria, Escherichia coli*, *Campylobacter, Mycobacteria, Clostridia,* and *Yersinia*) are known to be naturally present in raw feedstocks [52–55]. Although AD can significantly reduce microbial pathogens [56–58], the digestate may not be completely safe; especially at short solids retention time under mesophilic temperatures. Therefore, to prevent public health risks, digestate needs to be properly treated before application as a soil amendment [59]. The details of biogas spent slurry contamination and its treatment has been discussed elsewhere [60].

4. Status of biogas technology in developing countries

The earliest implementation of biogas, derived from decaying organic matter, is believed to originate thousands of years ago in Assyrian bathhouses for heating water [61]. It was not until the 1950s, however, when interest and rigorous research on the technology emerged and led to the advent of well-known digester designs like the Grama Laxmi III (proposed by Joshbai Patel in India, which later served as a prototype for currently popular floating-drum digester) [62]. Domestic digesters gained momentum in countries like China and India, where governments strongly supported the installation of household digesters. By 2007, there were about 26.5 and 4 million household digesters in China and India, respectively [61]. SNV, a Netherland Development Organization, has also actively promoted small-scale digester programs in various developing countries of Asia and Africa for the last 20 years. By the end of 2012, SNV managed to install over half a million household digesters, subsequently benefiting 2.9 million people by providing clean energy for cooking and lighting [63]. The total number of domestic digesters installed in selected developing countries are presented in Table 5, which illustrates a substantial increase in domestic biogas digesters in Africa during recent years. Compared to 2011, there was over 44% increase in domestic digesters installed in Africa in 2012 [63].

Among different digester designs, the two digester designs, namely the Chinese fixed dome digester (Fig. 2) and the Indian floating drum digester (Fig. 3) are the most common in developing countries. These digesters are usually built to convert human and animal wastes of one household to biogas for cooking and lighting. Typically, the average volume of the digester is approximately 5–7 m^3 and provides about 0.5 m^3 biogas per m^3 digester volume

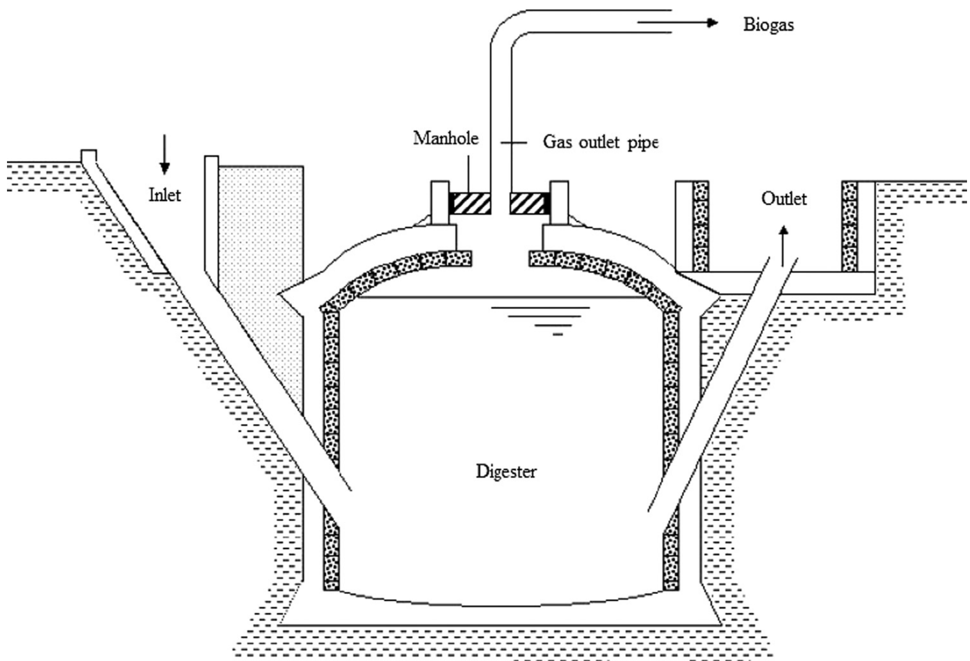

Fig. 2. Fixed dome (Chinese type) digester (adopted from Gunnerson and Stuckey) [66].

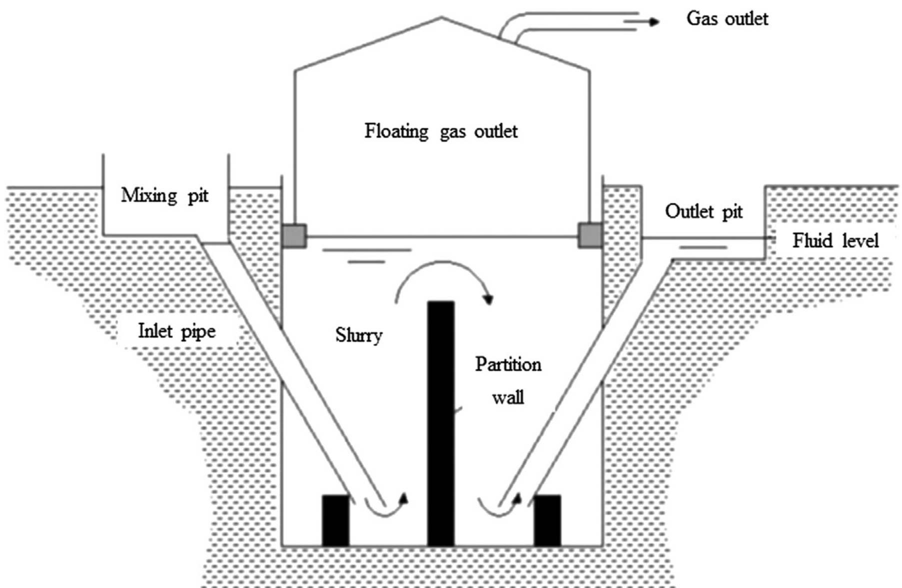

Fig. 3. Floating cover (Indian type) digester (adopted from Gunnerson and Stuckey) [66].

[64,65]. The floating drum digester is often constructed with concrete and steel; whereas the fixed dome digester is usually built with the locally available materials like bricks and stones. Only the cover in floating drum digester is above ground, and the rest of the components of both digesters are housed below ground.

The working principle of both digester designs is quite similar. Feedstock is added through the inlet pipe into the digester tank either directly or after mixing in a pit. The produced biogas is collected above the slurry and leaves the tank through a gas pipe connected to the top of the digester. The digestate (slurry) leaves the digester through an outlet pipe and is collected in an outlet pit or a displacement tank. The digester tank has either one compartment or two compartments (depending on whether it is a one or two stage configuration) where the substrate has an average retention time of 20–30 days. Floating drum digesters have a steel cover floating on the slurry which moves vertically to accommodate the constant biogas pressure. Higher gas pressures can be achieved by adding a weight on the top of the holder. In the case of fixed dome digesters, the gas is kept roughly at a constant volume while the pressure varies.

Both systems lack proper mixing and are operated without temperature control in developing countries. Moreover, there is no provision for removing settled inert materials that considerably reduce the effective volume of the digester over time. While the lack of moving parts and simple constructions make these digesters easy to operate and maintain, the cost of installation is still high for many rural farmers and requires skilled craftsmen; leading to limitations in the widespread adoption of this technology in developing countries [67,68].

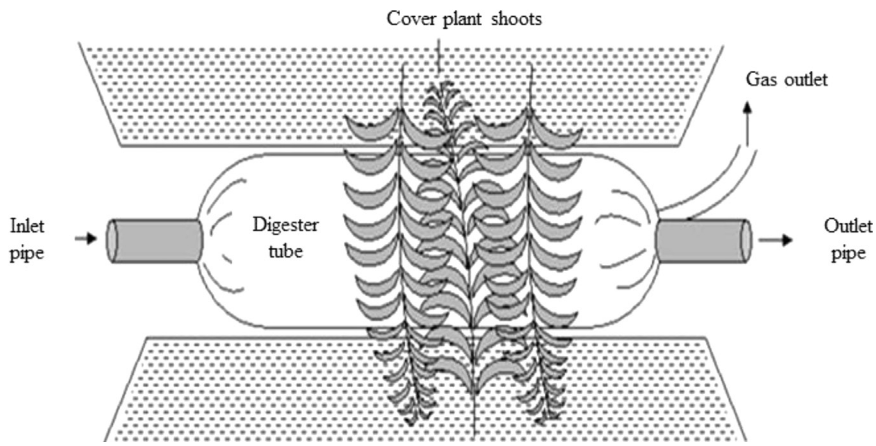

Fig. 4. Polyethylene tubular digester (adopted from Plöchl and Heiermann) [85].

In an effort to reduce installation costs as well as simplify the operation and maintenance of digesters, low-cost digesters are being constructed using polyethylene tubular film in developing nations [69–72]. The polyethylene tubular digesters (Fig. 4) are also characterized by a lack of mixing devices and/or heating systems to avoid sophisticated monitoring needs, and are fabricated using readily available materials: usually plastic bags for the main tank and polyvinyl chloride (PVC) pipes for biogas collection. Feedstocks pass through a tubular polyethylene or PVC bag (serving as the bioreactor), while biogas is collected by means of a gas pipe connected to the headspace. In order to maintain higher process temperatures and minimize overnight temperature fluctuations, in cold mountainous areas, the tubular plastic bag is often buried in a trench and covered with gable or roofed shed to provide crude insulation [73–79]. Design criteria and dimensions for the digester, trench and roofed shed depend on location; at high altitudes with colder temperatures a longer hydraulic retention time of 60–90 days is generally used for proper digestion [73]. Simple design, ease of installation and low specialized manpower demands make this technology both affordable and acceptable for household applications in developing countries such as Colombia, Ethiopia, Tanzania, Vietnam, Cambodia, Costa Rica, Bolivia, Peru, Ecuador, Argentina, Chile and Mexico where installation of the fixed dome and floating drum digesters have been reported to be too costly [69–71,80–83]. The relatively fragile nature of the polyethylene film, however, makes the digester prone to damage and has a lifetime of only 2–10 years [84] (Fig. 5).

Table 6
Biogas production potential of different organic sources.

Source	Specific biogas production (Nm^3/Kg_{DM})	References
Cattle manure	0.20–0.30	[101,102]
Pigs manure	0.25–0.50	
Chicken manure	0.31	
Sheep manure	0.30–0.40	[103]
Forage leaves	0.50	[101,102]
Algae	0.32	
Nightsoil	0.38	
Water hyacinth	0.40	
Slaughterhouse waste	0.30–0.70	
Vegetable wastes	0.40	
Grass cuttings from lawns	0.70–0.80	
Grass ensilage	0.60–0.70	
Hay	0.50	
Maize ensilaged	0.60–0.70	[103]
Rice straw	0.55–0.62	
Maize straw	0.40–1.00	
Potato mash, potato pulp, potato peelings	0.30–0.90	
Oilseed residuals(pressed)	0.90–1.00	
Molasses	0.30–0.70	
Leftovers (canteen kitchen)	0.40–1.00	
Waste from paper and carton production	0.20–0.30	
Organic fraction of municipal solid waste	0.10–0.93[a]	[104–107]

[a] $Nm^3/kg_{wet\ weight}$.

5. Biomass resources and biogas production potential

Biomass resources such as animal manure, human excreta, the organic fraction of municipal solid waste (OFMSW), sewage sludge, crop and forest residues, and energy crops can be used as a raw material for biogas production. In terms of net energy generation, biogas produced from these resources has been reported to be much more competitive than alcohol-based liquid biofuels [86,87]. In addition, AD also minimizes the release of GHGs along with allowing for the opportunity for organic waste remediation. The biogas production potentials of different biomass resources are summarized in Table 6. It should be noted that developed countries are already making use of millions of tons of organic wastes from municipal, industrial and agricultural processes for biogas production [86,88], but enormous volumes of organic waste remain underutilized in developing countries.

The specific characteristics of animal manure (as a feedstock for AD) vary with species and geography, but in general, manure has a high moisture content (75–92%) and volatile solids (VS) ranging from 72–93% of total solids (TS), as well as a good buffering capacity which makes it an ideal substrate for AD [89,90]. Furthermore, animal manure contains large and diverse microbial communities; hence anaerobic digesters receiving animal manure as a feedstock can be initiated without the addition of any external inoculums. However, because of a relatively low readily degradable organic content, animal manure has low biochemical methane potentials (BMP) and digestion can be slow. In addition, depending on manure type and freshness, a high concentration of NH_3, generated during digestion, creates unfavorable environment for methanogens [91]. The co-digestion of animal manure with feedstocks rich in carbohydrate but poor in nitrogen can significantly enhance biogas production.

Similarly, the composition of municipal solid waste (MSW) varies depending on the climate, income level, living standards, geography [92,93], domestic fuel supply [94,95], and collection

system. In developing countries, MSW is largely dominated by organic matter which accounts for over 55% of the total MSW. Although OFMSW contains less readily fermentable substrates and is typically deficient in nitrogen and phosphorus, it has a relatively high CH_4 potential when digested properly [96]. Pretreatments like particle size reduction and co-digestion with other nutrient-rich biomass (e.g. municipal sludge or animal manures) substantially increases CH_4 production from OFMSW [96,97].

Agriculture comprises a major fraction of the national economy in developing countries. These countries produce about 1,680 million dry metric tons of crop residues annually [98], a significant portion of which can be used for biogas production. Although the composition of crop residues varies significantly with crop type, in general, crop residues have relatively low moisture content, high VS content and variable amounts of readily fermentable constituents. Because most non-leguminous crops have a low concentration of available nitrogen, co-digestion of crop residues with animal manure or municipal sludge substantially improves CH_4 production [99].

Arguably, the best resources for biomethane production are food and food-processing wastes because of their high moisture (> 80%) and VS (95% of TS) contents. With the exception of meat waste, most food processing wastes are poor in nitrogen content; but are rich in readily fermentable organic matter. The co-digestion of food-processing residue with nitrogen-rich feedstocks (e.g., municipal sludge and animal manures) thus enhances system stability and overall CH_4 production [100].

6. GHG emission mitigation potential through anaerobic digestion of animal waste

In this section, we calculated the global warming mitigation (GWM) potential and carbon credit potential of biogas production from animal waste by considering (i) GHG emissions reduction potential through manure management (ERPMM), (ii) emission mitigation potential of produced biogas through traditional fuels (firewood and kerosene) substitution, (iii) emission mitigation potential of biogas slurry through nitrogen (N), phosphorus (P), and potassium (K) fertilizer substitutions. Finally, the net GWM potential was derived by implementing the following equation:

GWM potential = Global warming potential (GWP) of CH_4 and N_2O emission reduction from animal waste management
+ GWP of CO_2 emission reduction from firewood and kerosene substitutions
+ GWP of CH_4 emission reduction from firewood substitution
+ GWP of CO_2 emission reduction from N, P and K fertilizer production
+ GWP of N_2O emission reduction from N fertilizer application
− GWP of CH_4 leakage from biogas digester
− GWP of CH_4 emission from biogas burning
− GWP of CO_2 emission from biogas burning

6.1. GHG Emissions Mitigation Potential through Manure Management (ERPMM)

The methane emission potential from animal waste was calculated as per the US EPA guidelines [109]. Data on the population of animals by type (Table 7) were obtained from FAOSTAT [110]. Total dry matter (kg/head/day), volatile matter (kg/head/day) production and maximum methane production capacity (m^3 CH_4/kg VS) by animal type for developing countries (Table 8) were obtained from the US EPA [109]. The methane emission index (kg/head/year) by animal type and region (Table 9) was calculated by taking the average values of the countries for which such values were available from the US EPA [109]. Finally the total methane emission potential was calculated by multiplying methane emission index by the total number of animals by type.

In the absence of specific guidelines for the calculation of nitrous dioxide (N_2O) emission from animal waste and methane emission from human waste, values given by Bhattacharya et al. [111] were used for all regions (see supplementary material in Table S-1). CO_2 emissions from animal waste was not calculated since the current Intergovernmental Panel on Climate Change (IPCC) guideline for GHG emission from animal waste does not require the calculation of such values [111].

Because only a fraction of total animal waste is recoverable for biogas generation, the waste recovery percentages for different animals have been summarized in Table 8. In this analysis, waste recovery rates for buffalo and duck were assumed to be similar to cattle and chicken, respectively. Camels, horses, asses and goats are usually kept in open places and individual holdings are small, consequently waste from these animals was assumed to be non-recoverable [111]. ERPMM was calculated by using equations described by Yu et al. [113]. In this situation, the N_2O emission factor and manure

Table 7
Livestock and human populations (millions).

Region	Chickens[a]	Ducks[a]	Buffaloes[a]	Cattle[a]	Pigs[a]	Sheep[a]	Human[b]
Africa	1494	18	4	275	27	294	987
Caribbean	201	< 1	< 1	9	4	3	42
South America	2037	8	1	347	57	76	385
Eastern Asia (less China and Japan)	153	15	NA	6	12	19	94
China	4703	769	23	84	451	129	1325
Southern Asia (less India)	1078	29	37	77	1	96	579
India	613	35	107	172	14	66	1150
South-Eastern Asia	2314	225	15	47	71	11	576

Note: Geographical regions based on United Nations Statistics Division.
[a] [107].
[b] [108].

Table 8
Manure characteristics for selected animals.

Animals	VS (kg/head/day)[c]	DM (kg/head/day)[c]	Waste recovery (%)[a]	Specific biogas production (Nm^3/kg_{DM})[b]	Maximum methane production potential for developing countries (Nm^3/kg VS)[c]
Buffaloes	2.01	2.53	50[f]	0.25	0.10
Cattle[d]	2.67	2.86	50	0.25	0.11
Chickens	0.02	0.04	100	0.31	0.24
Ducks	0.02	0.05	100[f]	0.31	0.24
Human[e]	0.06	0.09	100	0.38	0.20
Pigs	0.59	0.66	23	0.37	0.29
Sheep	0.30	0.33	33	0.35	0.13

[a] [112].
[b] Average values (Table 9) was taken.
[c] [109]
[d] Average of dairy and non-dairy cattle.
[e] [111].
[f] [*Note*: In the absence of information on specific biogas production of buffaloes and ducks waste, specific biogas production of waste from cattle and chicken were assumed to be similar to specific biogas yield of buffaloes and ducks waste, respectively].

recovery percentage for animal type were taken into consideration, which were not included in the equations given by Yu et al. [113].

It was determined that out of an annual total 1860 million dry metric tons animal waste and human excreta generated, 1068 million dry metric tons are available for AD (Table 10). Proper management of the animal manure and human excreta would annually prevent 418 million metric tons of CO_2 equivalent GHG emission to the atmosphere (Table 11).

6.2. GHG emission mitigation potential of produced biogas

As discussed previously, the replacement of traditional fuels such as firewood and kerosene, the most commonly used fuels in developing countries, with biogas can result in an overall GHG emission reduction. The total biogas production potential was calculated using average values for specific biogas production by animal type (Table 8). In this calculation, we considered lower specific biogas production potential values than the values reported in various published papers [111,114] because most of the household biogas plants in developing countries do not operate under optimal conditions. Kerosene and firewood equivalents of the produced biogas were then calculated using the calorific values of these fuels. All of the coefficients used in the calculation are summarized in the supplementary material in Table S-2.

Calculations show that available animal wastes and human excreta have the potential to produce 278 billion Nm^3 of biogas per year. The energy equivalent of this produced biogas is estimated to be 5818 PJ/year (Table 10).

Based on the assumption that 80% of the produced biogas would be used to replace firewood and the remaining 20% to replace kerosene used in the households cooking and lighting [114], it is estimated that the produced biogas has the potential to substitute 727 million dry metric tons of firewood and 42 billion liters of kerosene per year. Furthermore, the substitution amount of both firewood and kerosene calculated above will annually curtail 1235 million metric tons of CO_2 equivalent GHG emissions into the atmosphere (Table 11).

6.3. GHG emission mitigation potential of biogas slurry

GHG emission mitigation from biogas slurry results due to use of slurry as a substitute for chemical fertilizer. In AD only C, H and O components of substrate are lost in the form of CH_4, CO_2 and H_2O, and all the other essential nutrients such as N, P and K, and trace elements are retained within the slurry [115]. The amount of substrate converted into biogas was calculated by multiplying the specific biogas yield with the biogas density (see supplementary material in Table S-3). N, P and K fertilizer equivalents of the biogas slurry were derived by assuming that the slurry contains 1.4% N, 0.5% P and 0.8% K on dry weight basis [116,117]. CO_2 emissions during the production and application of these chemical fertilizers were calculated by using equation given by Schlesinger [118], Lal [119], and Pathak and Wassmann [120].

It is estimated that the use of recoverable animal waste in biogas production results in the generation of 690 million dry metric tons digestate per year. The chemical fertilizer equivalent of the produced digestate was calculated to be 10, 8, and 6 million metric tons of N, P, and K per year, respectively (supplementary material in Table S-4). Thus, the use of the digestate as a substitute for chemical fertilizer will mitigate nearly 36 million metric tons of CO_2 equivalent GHG emissions per year (Table 11).

Table 9
CH_4 emission index (kg/head/year) [109].

Animals	Regions				
	Africa	Caribbean and South America	Eastern Asia, Southern Asia, and South-Eastern Asia	China	India
Chicken	0.105	0.132	0.143	0.126	0.150
Duck	0.125	0.125	0.119	0.125	0.119
Buffalo	4.951	4.951	4.308	4.951	4.555
Cattle[a]	5.350	5.853	7.175	8.622	5.790
Human	1.437	1.437	1.437	1.437	1.437
Swine	2.944	3.130	4.462	4.431	3.099
Sheep	1.065	1.241	1.216	1.253	1.253

[a] Average value for dairy and non-dairy cattle.

Table 10
Animal waste availability and biogas production potential.

Region	Animal waste available for digestion (million dry metric tons/year)	Potentially available biogas (million Nm^3/year)	Energy production potential of biogas (Peta Joule, PJ/year)	Kerosene equivalent of 20% of biogas (million L/year)	Firewood equivalent of 80% of biogas (million dry metric tons/year)
Africa Total	215	54,671	1143	8166	143
Caribbean	9	2495	52	373	7
South America	233	56,200	1175	8394	147
Eastern Asia (less China and Japan)	10	3003	63	447	8
China	216	61817	1293	9233	162
Southern Asia (less India)	98	25,522	534	3812	67
India	191	48,178	1007	7196	126
South-Eastern Asia	95	26,338	551	3934	69
Total	**1068**	**278,224**	**5818**	**41,555**	**727**

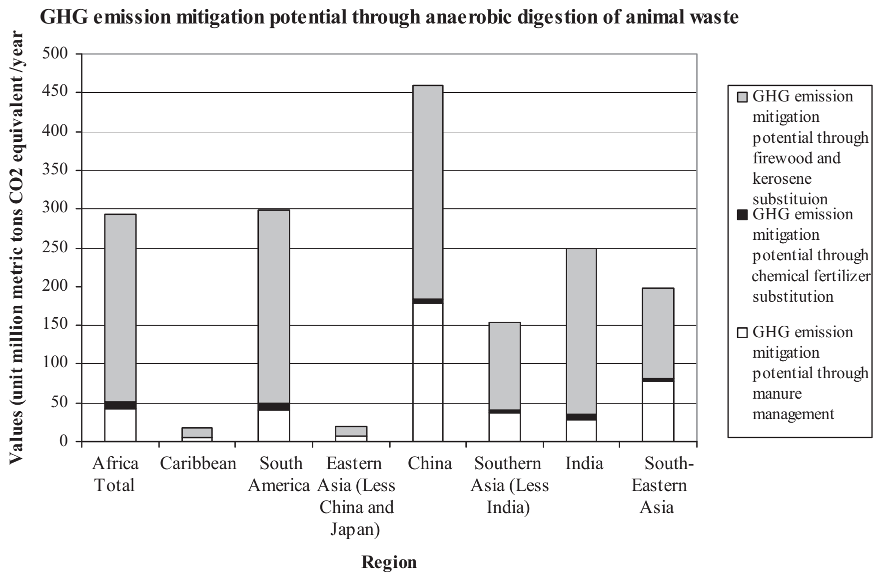

Fig. 5. GHG emission mitigation potential through anaerobic digestion of animal waste.

Table 11
GHG emission mitigation potential (unit: million metric tons CO_2 equivalent/year).

Region	GHG emission mitigation potential through chemical fertilizer substitution	GHG emission mitigation potential through animal manure management	GHG emission mitigation potential through firewood and kerosene substitution	Net GHG emission mitigation potential
Africa Total	7	43	243	293
Caribbean	<1	6	11	17
South America	8	41	249	299
Eastern Asia (less China and Japan)	<1	6	13	20
China	7	178	274	459
Southern Asia (less India)	3	37	113	153
India	7	29	214	249
South-Eastern Asia	3	78	117	198
Total	**36**	**418**	**1235**	**1689**

Summarizing in brevity, 1689 million metric tons CO_2 equivalent GHG emission can be mitigated annually from the developing regions through the utilization of available animal waste and human excreta for biogas production (as a substitute for firewood and kerosene) and subsequent utilization of biogas slurry as an organic fertilizer. Of the total, annually 459, 299 and 293 million metric tons CO_2 equivalent GHG emissions can be mitigated from China, South America, and Africa, respectively (Table 11) (Fig. 5).

6.4. Carbon trading potential

A provision for carbon trading has been mentioned in Article 17 of the Kyoto Protocol. Under this provision a country with a carbon surplus is assigned an amount unit – emission permitted to them but not used – which can be traded to countries exceeding their emission targets. Prices of carbon credits range from US$ 5–20 per metric ton CO_2 equivalent, depending on the volume and timing [121]. However, such credits are being sold in international carbon credit market at the rate of US$ 5–8 per metric ton CO_2 equivalent [122]. In the following calculations, the carbon credit rate of US$ 6.5 per metric ton CO_2 equivalent, the average of the current carbon credit rate (US$ 5–8 per metric ton CO_2 equivalent), is considered.

Table 12
Annual carbon credit potential (Unit billion US$/year).

Region	Carbon credit potential
Africa	2
Caribbean	<1
South America	2
Eastern Asia (less China and Japan)	<1
China	3
Southern Asia (less India)	1
India	2
South-Eastern Asia	1
Total	**11**

Calculations show that the market value of GHG emission reduction (1689 million metric tons CO_2 equivalent) after the adoption of biogas plants would be around US$ 11 billion per year. Assuming the average per unit installation cost of the household level biogas plant to be about US$ 1000 [123–126], the generated revenue would be sufficient to cover the installation cost of 11 million household biogas plants per year in developing countries (Table 12).

7. Opportunities and challenges of biogas development in developing countries

7.1. Opportunities

The United Nations (UN) Commission on Sustainable Development (CSD) identified access to basic energy services as an essential element of sustainable development. According to CSD, "*to implement the goal accepted by the international community to halve the proportion of people living on less than US$* 1 *per day by* 2015*, access to affordable energy services is a prerequisite*" [127]. There is a strong correlation among energy availability and education, health, urban migration, empowerment, local employment and income generation, and an overall improvement in the quality of life [128]. Understanding and taking into account the current status of developing nations, biogas technology has implicit potential in improving waste management, producing clean energy, reducing workload (especially for women and children), and creating employment opportunities for communities at the local level. A considerable amount of renewable feedstocks in the form of animal manure, crop residues, food and food processing wastes, and OFMSW available in developing countries can be utilized economically for biogas production. In addition, resources currently being used in the management of such wastes can be diverted for establishing biogas plants and harness clean energy in the form of biogas. AD of animal manure and other biogenic wastes offer several environmental, agricultural and socio-economic benefits through the fertilizer value of the digestate, considerable reduction in odor and inactivation of pathogens, and ultimately biogas as a clean renewable fuel for multiple end applications. In addition, as mentioned previously, the widespread application of biogas technology in developing nations has tremendous potential in reducing GHG emissions thereby creating new possibilities of carbon trading in the global market. The revenue generated through carbon trading could be deployed for further research, development and dissemination of biogas technologies domestically.

7.2. Challenges

Despite its significant economic, environmental, health and social merits, biogas technology, with some exceptions, has not permeated much into the rural communities of developing countries. One of the major barriers for the widespread diffusion of this technology is the high installation and maintenance costs. Depending on the region and type, costs of a typical household level digester varies from US$ 435–1667 [123–126]. This level of investment is far out of the financial reach of many rural households. Moreover, the economic structure in many developing countries favors fossil fuels over renewable fuels. For example in China, the cost of power generation using bioenergy or biomethane is now about 1.5 times greater than the cost of power generation using coal [129], overlooking of course, the irreparable environmental damage and opportunity costs associated with using fossil based fuel.

Inadequate expertise for construction and maintenance of biogas plants is another constraint hindering the dissemination of biogas technology in the region. Although energy has been identified as being critical for development, energy has not received significant attention in policy debates of developing nations. Moreover, energy technologies and their implementation are not taught in depth in most engineering and technical courses currently offered at universities and colleges in the region. Thus, there are hardly any technical/vocational schools that train manpower in various essential aspects of renewable energy technologies including but not limited to biogas technology. In many rural communities, the locals may even lack access to formal education altogether [68]. Even though subsidies and program have been implemented in the past, a number of biogas projects have failed due to an inability for proper management. For example, out of 26.5 million household biogas plants in China, only about 60% were operating normally in the year 2007 [130]. Such a low success rate, not surprisingly, discourages neighboring countries to install similar systems.

Water is essential for both the installation and operation of biogas plants, but is often taken for granted in developed nations and is overlooked as a challenge in many contemporary reviews. At least 60 l of water is required for a cow per day as well as an additional 60 l/day to add into the digester [131]. Only a small percentage of the population in mountainous and African regions has consistent access to sufficient water. Lack of adequate water for operating biogas plants in other areas is a significant hindrance for the widespread adoption of biogas technology [132]; particularly if the water source is distant from individual households and/or is limited during changing seasons. In addition, because optimal temperatures required for biogas production through AD is between 35–37 °C (mesophilic) or about 55 °C (thermophilic), existing floating drum and fixed dome type digesters are unsuitable for biogas production in cold mountainous regions of some developing countries like China, Nepal and northern India (which often have a steady water supply).

8. Recommendations

8.1. Co-digestion of feedstocks

One recommendation subtly implied throughout this manuscript is the co-digestion of different organic feedstocks to cope with feedstock scarcity (if relevant) and improve biogas production. The co-digestion of animal manure with suitable organic wastes such as crop residues, by-products from food processing industries, OFMSW and bio-slurries from biofuels processing industries directly results in increased biogas production and energy sales, savings related to organic waste treatment, improved fertilizer value of the digestate and a reduction of GHG emissions [133–135].

8.2. Government policy

Because installation costs are one of the major barriers for wider adoption of the biogas technology, to increase public acceptance and the affordability of the technology, construction costs should be reduced, and the direct and indirect costs and benefits of biogas technologies need to be quantified and valued [136]. Household expenses might be reduced either by developing low cost technology or by providing government subsidies. In countries like China, India and Nepal, biogas programs developed quickly because of substantial financial and technical support provided by the government and various aid agencies [66,137,138]. Notably, in those same countries, the installation of new biogas plants declined dramatically when the governments reduced subsidies and programs [139–141]. Financial sources to provide such aid could be generated by developing biogas plants across the country as clean development mechanism (CDM) projects. Developing countries like Nepal, where the per capita biogas plant is the highest in the world, has already developed biogas plants as CDM projects, and the revenue generated from such projects has been implemented for further dissemination of biogas technology in the country.

8.3. Micro-financing

Even with the help of government and aid agencies, people still might not afford to cover the capital costs of installing household digesters, particularly in remote locations. In order to improve the rural populations′ access to biogas technologies, provisions for financing services (soft loans) should be made available. One avenue to explore may be micro finance institutions established in target areas so that poor households have an easy access to an appropriate range of financial services. For example, in Nepal – a country with the highest per capita household digester – over 260 microfinance institutions are providing credits for households who are unable to pay the upfront cost of biogas system [142]. Such institutions include but are not limited to development banks, microfinance development banks, multi-purpose cooperatives (e.g., milk vegetable, and women cooperatives), and savings and credit cooperatives. Such institutions being closer to the borrower will reduce the time needed for debt management and education. Also, poorer populations, which typically hesitate to deal with big financial institutions, may find it more comfortable to deal with smaller entities like cooperatives [128].

8.4. Awareness program

Education is arguably among the greatest challenges impeding the progress of biogas technology in developing nations. To establish biogas as a viable and sustainable option for developing countries, it is important to educate the people about the potential economic, health, social and environmental merits of biogas technology. There is a need to develop specialized programs that bring awareness and disseminate knowledge to a wide audience through a variety of mass media and multi-stakeholder dialogs. More importantly, programs for technology and knowledge transfer from the countries where biogas technologies have already been successfully implemented to countries around the globe should be promoted.

9. Summary

Some three billion people around the world, primarily in rural areas of developing countries, rely on traditional biomass resources for energy, and in metropolitan cities, billions more import expensive fossil fuels to meet their energy needs. However, the excessive and poor use of biomass coupled with an ever increasing dependency on imported fossil-derived resources has resulted in negative impacts on public health, the environment and the already fragile economy of developing countries. Within this context, advocating for sustainable and affordable energy options, namely in the form of biogas, is required for continued development in these regions. AD is a clean, simple energy technology, and is less costly than comparable renewable technologies. Thus, for developing countries in particular, biogas has a great potential in terms of available (and underexploited) feedstocks, job creation, reduced environmental impacts, and providing clean and reliable energy to improve the current quality of life. Although AD has been used for many years, this technology continues to harbor significant gaps in knowledge related to the implementation of such systems in varying geographies. Modernization (which should fulfill the criteria of being cheap, robust and easy to operate) and rapid dissemination of this technology is essential to harness the inherent potential that is currently underutilized and unexploited. With continued research and attention placed on developing regions of the world, the benefits of a more sustainable way of life and economy may be realized at both the domestic and international levels.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2013.12.015.

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